Cervical Spine Motion During Ambulance Transport: Effects of Driving Task and Spinal Precautions

by

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Dedications

To my mother, whose cervical spine fractures influenced the direction of my studies.
To Dr. Pryce, without whom none of this would have been possible.
To my committee, for their patience, guidance, and inspiration.

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Abstract

Problem: Spinal precautions designed to protect an injured spine are associated with deleterious effects and questionable efficacy. The purpose is to determine the influence of vehicle motion on head/neck motion (acceleration & angular displacement) during ambulance transport and to compare the effectiveness of two spinal precautions protocols.

Methods: Balanced-order, repeated measures comparison of two spinal precaution conditions on head-neck (H-N) kinematics during various ambulance driving tasks (7 tasks, 4 speeds). Acceleration (peak and RMS) and orientation (peak) of the head, sternum, and ambulance will be measured by accelerometers.

Results: The overall effect of spinal precautions was small. H-N motion varied across speed and driving task, with a large range of angular displacements [4 to 34°] and accelerations [1.5 to 13.5m/s²].

Conclusions: For most driving tasks and speeds, SI and SMR do not differ greatly in their efficacy. Both protocols allowed for considerable amounts of motion, warranting improvements to spinal precautions, and further investigation into ambulance driving.

Review of Literature

Introduction

Each year, more than 4,300 Canadians sustain spinal cord injuries, and countless more with suspected injuries receive spinal precautions[1]. Spinal precautions are undertaken to protect a potentially injured and unstable spine[2]. Traditionally, all suspected neck injuries were treated with spinal immobilization (SI) – a protocol consisting of application of a rigid cervical collar and placement on a long rigid backboard with straps and head blocks[3]. Recently, this practice has been questioned, in part due to increasing evidence of the deleterious effects of SI, such as increased treatment time[4], delayed transport[5], pressure sores[6], respiratory difficulties[7], and discomfort eliciting movement in a conscious patient[8]. Moreover, SI may not be possible for patients with anatomical deformities[9] (e.g. advanced spondylosis in elderly patients). Finally, the effectiveness of SI at preventing secondary injuries has been questioned[10].

Consequently, in many jurisdictions, the use of a backboard has been restricted to high-risk trauma patients and/or extrication procedures[5],[11], and many patients receive spinal precautions in the form of spinal motion restriction (SMR) protocols, usually consisting of a rigid collar and stretcher mattress. The revised SMR protocols encourage EMS providers to transport most patients with potential spine injuries in either a full or semi-reclined position on a stretcher mattress, with a cervical collar only[12]. Emergency medical services in Saskatchewan and Alberta have already incorporated these ideas into their pre-hospital care protocols, and will be transporting the majority of low-risk, potential spine-injured patients with a collar only[12,13]. With this change in practice comes a need to ensure incorporation of SMR protocols does not expose patients to an increased risk of secondary injury during prehospital emergency care (i.e. due to less effective c-spine stabilization).

Surprisingly, the vast majority of investigations on the efficacy of spinal precautions have focused only on patient extrication[14–16] and not on the subsequent transport and in-hospital periods. This is likely related to the assumption that once secured to the immobilization devices, patients are completely motionless until removal from the apparatus at a primary care facility. Multiple factors may contribute to movement during transport, including patient combativeness[17], poorly fitted cervical collars[18], and/or equipment failure[19]. However, the primary determinant of patient motion during transport is likely vehicle motion, related to driving manoeuvres and road surfaces. In fact, emergency personnel in Manitoba have voiced their concerns regarding the impact of road conditions on patient comfort, and the ability of EMS personnel to provide care during transport[20]. It would be anticipated that vehicle motion, and therefore patient movement, would vary across different driving tasks (i.e. turns, rapid accelerations), as well as road conditions (i.e. pot holes, traffic calmed roadways), however this remains to be thoroughly explored.

Only two studies have examined the effects of vehicle motion on head-neck (H-N) displacement in participants receiving SI[21,22]. Both investigators reported a substantial amount of uni-axial angular displacement between the head and trunk (8° and 18°), despite the use of SI – displacements that are equivalent to those observed during maximal voluntary efforts in SI[23]. While these studies revealed that substantial amounts of displacement can occur during transport (with SI), the validity of the results is limited by the use of simulated, rather than actual, vehicle motion[21], or the lack of discrete, quantifiable driving task parameters complementing the neck angular displacement findings[22]. The prehospital literature is devoid of any comprehensive examination of transport-related neck kinematics during actual driving tasks or road conditions in patients receiving SI. Furthermore, no studies have compared the amount of transport-related motion between conventional SI and the revised, collar-only protocols (SMR).

The purpose of this work is to determine the influence of vehicle motion on H-N motion during ambulance transport and to compare the effectiveness of two motion reduction protocols (SI vs. SMR). This is highly relevant to nearly all patients receiving spinal precautions and addresses a significant gap in the understanding of cervical spine injury management.

Epidemiology of Spine Injuries

An estimated 86,000 Canadians are living with a spinal cord injury (SCI), with over 4,300 new injuries occurring each year[1]. The incidence of cervical spine injuries in developed countries is estimated at 11.5 to 53.4 per million of inhabitants[24], with one of the highest incidence rates observed in Alberta, Canada (52.2 per 1 million)[25]. Spinal precautions are a fundamental component of pre-hospital care for all patients with SCI, as well as the countless more with suspected spinal injuries (e.g. those with high energy mechanisms of injury).

In most cases, injuries to the spine follow blunt trauma and/or rapid accelerations of the head relative to the trunk (i.e. whiplash)[26]. This results in the forceful displacement of vertebral segments, leading to the rupture of the surrounding musculature, ligaments, and spinal cord[27]. The cervical spine is a particularly vulnerable segment of the spinal column, contributing to between 41% and 75% of all SCIs[28]. It is worth noting that 50% of patients with SCI have an incomplete lesion and limiting injury progression is vital for such patients, as SCIs are associated with high personal, bio-psychological, and socio-economic consequences[1]. Further, treatment of SCI is complex and places a heavy burden on the health care system, with estimated costs of between $1.5 million for incomplete paraplegia and $3.0 million for complete tetraplegia[29]. The estimated annual economic burden associated with traumatic SCI in Canada is $2.67 billion, related to secondary complications needing hospitalization (e.g. urinary tract infection and pressure sores), home care services, extra physician contacts, and increased prevalence of other health problems secondary to SCI (e.g. psychological disorders)[29]. Considering these consequences, limiting the potential for further damage to the spine is of paramount significance during prehospital care. In fact, spinal precautions are applied to all patients with suspected SCI, accounting for as many as 5% of all trauma patients treated pre-hospital[30].

Management of Suspected Spine Injuries

The purpose of spinal precautions is to prevent further, potentially harmful movement of the cervical vertebrae. This movement may be induced actively by patients, or passively by emergency personnel and vehicles. Although the exact type of H-N motion (displacement and/or acceleration) leading to additional traumatic injury remains unclear, it is believed that by stabilizing the head, neck, and trunk, the risk of secondary injury is reduced[21]. For instance, it is well-established that increased range of motion observed at the head results in more motion in the cervical spine[31] and that this increased motion may aggravate neurologic outcomes[32]. As many as 16% of spinal cord injuries experience deterioration outside of hospital[10].

In order to limit injury progression due to excessive H-N motion, specific devices and protocols have been developed. The most common form of spinal precautions is conventional spinal immobilization (SI), accomplished by securing patients to a rigid surface combined with the use of straps, head blocks, and a cervical collar. This procedure was originally intended to keep the head and neck from sagging during extrication[33]. Cervical collars provide rigidity to the injured cervical segment[34] and are designed to be adjustable to the patient's neck length and width[35]. Multiples studies report a significant reduction in displacement with cervical collar[34–36], in comparison to no intervention.

The other essential device in SI is the rigid backboard, which is also intended to aid extrication by freeing the hands of rescuers from actively holding spinal precautions, and has been widely adopted as the preferred method for handling and transporting patients[37]. To further increase the stabilization of the head and neck, foam blocks or occasionally rolled towels[17] are placed on the lateral aspect of the patient's cranium and reduce neck lateral-flexion and rotation motions[23]. An alternative to the rigid backboard is the vacuum mattress splint (VMS) which was developed to provide better overall protection of an injured casualty, but requires more personnel to lift and move it[38].

Limitations and Deleterious Effects of SI

One of the issues surrounding SI lies in asserting whether neurological deterioration is due to the "natural disease process" or is caused by inappropriate movement restriction[2]. Excluding mechanical injury, spinal injuries can deteriorate due to haematoma, cord oedema, hypotension, inflammation, and vascular changes such as reduced microcirculation[39,40]. While preventing excessive vertebral movement is important in principle, the biomechanical and physiological principles underlying SCI deterioration are somewhat controversial. For instance, even with good immobilization of the spine, neurological deterioration occurs in around 5% of SCI patients[41]. Further, authors of a 2006 systematic review concluded that the effect of SI on mortality, neurologic injury, spinal stability, and adverse effects in trauma patients remains uncertain[42]. In fact, the authors suggest that SI may have little or no effect on outcomes, possibly because large forces are required to cause injury and further movement will not worsen existing damage. Similarly, White & al. assert that SI is rarely effective, and more reliant on patient compliance than application parameters[43].

Additionally, many investigators have acknowledged that SI may be over-prescribed. In a 1988 study, it was estimated that more than 50% of alert, cooperative trauma patients were transported with full SI, despite no complaints of neck or back pain[44]. This highlights the necessity of improving screening procedures to increase the efficiency of emergency medical services. Current protocols also emphasize control of the neck above all else, despite the possibility that the effectiveness of such procedures is also limited by trunk movement[21]. That is, spinal stability will not be achieved if the trunk is allowed to move relative to the fixed cranium and neck (versus a poorly stabilized head/neck moving relative to a fixed trunk). Studies have shown a significant improvement in lateral motion restriction with the addition of abdominal straps[17]. In this regard, the use of straps is a very important, yet often overlooked factor in prehospital SI and more attention should be given to inferior, larger body segments.

In other cases, full SI is sometimes contraindicated or impossible to perform for certain patients. For instance, spinal deformities such as ankylosing spondylitis require precautions, as extension of an ankylosed and kyphotic cervical spine during application of conventional SI can result in neurologic deficits[45]. In these cases, pillows are usually used to support the head. Cervical spine alignment in a similar flexed position is essential during SI of patients with ankylosing spondylitis, but is not part of the standardized protocol[40]. Cervical collars may also lead to an increase in intracranial pressure in patients with head injuries, leading to detrimental effects on the injured brain[46]. Application of SI devices may also impede access to the patient's airway. This is important as respiratory failure is the cause of 6% of trauma fatalities[47] and any factors that might be increasing the frequency of respiratory failure or impeding its management should be carefully examined[48]. For example, advanced airway management (including endotracheal intubation) is more likely to fail in the presence of a collar[49]. SI cannot be performed in the presence of gunshot wounds[50] or other penetrating trauma[51], as cervical collars and rigid backboard may interfere with treatment. In these circumstances SI is believed to increase the risk of death due to obscuring clinical indicators, blocking access to the injury site, impairing intubation, reluctance to remove a cervical collar to treat life-threatening injuries, and impedance of medical care[52,53,54].

Beyond their questionable effectiveness, spinal precautions are associated with a growing number of deleterious effects. For instance, by impairing blood flow, cervical collars may restrict venous drainage[55,56], which can lead to complications in patients with serious head injuries. In addition to impairing airway access[57,58], cervical collars can contribute to pressure sores around the neck and head[45] and lead to discomfort. Consequently, Holla et al. deemed the addition of a rigid cervical collar to patients already secured with head blocks "unnecessary and potentially dangerous"[59]. In fact, addition of collars may elicit movement due to discomfort[57,58,60] and more shockingly, may exacerbate spinal instability in some patients by causing an abnormal distraction to an injured spinal segment[61]. As well, studies on cadavers where spinal instability was created surgically by cutting stabilizing structures in the neck have found collars to be ineffective at preventing H-N motion during patient handling[62].

Similar to collars, the most recognizable downside to backboard use is discomfort[63]. Lower back and cervical pain has been reported to persist in previously pain-free, healthy volunteers for up to 24 hours after one hour of SI on a backboard[64]. Other issues related to backboard use include the development of pressure ulcers[65] and respiratory compromise[66]. A long backboard combined with straps has been shown to significantly impair respiratory function and increase respiratory efforts[64]. Even in 'ideal' circumstances (e.g. a stable patient, uncomplicated trauma), full SI is associated with tissue ischemia[67]. In fact, increased discomfort and pain may mimic signs of more serious spinal trauma and lead to multiple radiographs being taken, further increasing the total treatment time, and unnecessarily exposing patients to radiation[68]. Finally, non-cooperative patients may exert more force on their spine by fighting the restraints[37]. For those reasons, in some jurisdictions the backboard is used only as an extrication device and use during transport is discouraged.

Lastly, in addition to the undesirable effects above, one important concern with full SI is its time-consuming nature[30]. Deterioration of the injured spine is time sensitive, which renders long SI protocols not only questionable, but potentially dangerous due to the delayed care. For example, the longer it takes treating staff to suspect a diagnosis of SCI, the greater the possibility of neurological deterioration occurring in that patient[2]. Full SI may hide underlying injuries[69] and complicate assessment[50]. In fact, a cohort study in New South Wales, Australia, found that patients who reached a spinal unit after 24 hours, compared to patients who reached the unit in less than 24 hours, were 2.5 times more likely to develop one or more secondary complications, including pulmonary embolism, deep vein thrombosis, and pressure ulcers[70]. Early patient transfers (8-24 hours) to spinal care units and effective resuscitation have been demonstrated to lead to better neurological outcomes[71]. Ahn et al. further insist that transport should occur in the first 24hrs following injury[72]. In that effort, limiting the number of interventions would reduce total time spend at the scene, and help patients reach the emergency room sooner.

Spinal Motion Restriction

In view of the issues previously mentioned, improvements to the standard of care have been sought by various medical services. In North America, efforts have largely been directed towards limiting the use of rigid backboards. For example, Alameda County EMS were among the first to revise their spinal immobilization protocol in 2012, and instead proposed a Spinal Motion Reduction (SMR) plan to limit the deleterious effects of SI[73]. The California paramedicine service further states that "hard back-boards should only have limited utilization" during movement of patients needing SMR[73]. Numerous other states are implementing SI changes, such as Maryland where the backboard will be eliminated for patients with penetrating trauma[37], as well as Ohio and New Mexico, where patients with suspected SCI will be transported with only a cervical collar on the ambulance stretcher[37,73].

More recently, in Canada, the Saskatchewan College of Paramedics was among the first to question current protocols and implement changes in favor of partial or selective spinal motion reduction[12]. Their efforts have been aimed at reducing the use of backboards, unless absolutely necessary (e.g. extraction procedures & high likelihood of a displaced fracture). A study conducted by Vaillacourt et al. suggests that up to 40% of trauma patients could be transported without SI, following the Canadian C-spine Rule (CCR) criteria[74]. According to the CCR, SI should only be performed if patients are deemed to be at "high risk" (defined as a dangerous MOI, numbness/tingling in extremities, > 65 years of age), if they are not ambulatory, present immediate (not delayed) neck pain and/or midline cervical-spine tenderness, or are unable able to perform neck rotation (45° to either side). In the absence of those factors, fewer precautions can be taken while transporting them as the possibility of unstable spine injury and spinal cord trauma are reduced. It has been suggested that in these cases, a large amount of force is required to injure the spinal cord and movements during transport are unlikely to generate sufficient energy to result in additional injury[30]. However, these implications are derived from cadaver studies, and have not been verified, nor measured in actual patients. Further research is needed to support these assertions.

Outcome Measures in SI

Given that H-N motion restriction is the main objective of SI, it is not surprising that displacement is the most common outcome in studies examining spinal precaution tools and protocols[17,34,75]. Displacement is typically quantified as the relative change in angular position of the cranium in relation to the sternum[76,77]. Angular displacement has been assessed using a variety of methods, including handheld goniometers[78,77,80]. This method presents the advantages of being economical and providing immediate measurements, however it is a relatively crude instrument restricted to a single measurement (non- continuous). More commonly, video-based measures have been employed[14,17], allowing researchers to quantify the angular displacement of the head across multiple planes. One limitation of most video-based systems is a comparatively low sampling rate (24 or 30 Hz) and/or limited ability to extract continuous measurements (across all frames), factors that limit estimation of other kinematic variables such as velocity or acceleration. While more advanced 3D-motion capture systems can provide continuous estimates of displacements, velocity and acceleration[14], both video-based and 3-D motion capture systems require a clear line of sight, large fields of view, are generally restricted to the laboratory setting and are not practical for transport scenarios.

The inclusion of acceleration measurements (combined with angular displacement) can provide a more complete understanding of head and neck kinematics, and is commonly used in other areas, such as physical activity[81], gait[82], and head trauma[83]. Only two studies have examined acceleration in SI, one examining voluntary motion[23] and the other medical utility-vehicle transport[84]. During voluntary motion it was shown that SI appliances likely attenuate displacement to a greater extent than acceleration, where despite noticeable H-N motion restriction, participants were still able to produce substantial voluntary accelerations of the head, up to $6.8 m/s^2$ [23]. Principles of Newtonian mechanics state that force is proportional to acceleration; consequently, examining large accelerations over small displacements might be more clinically relevant than low accelerations occurring over larger displacements. For instance, new findings specific to cervical spine injuries indicate an association between increased acceleration at impact and an increase in injury severity[85]. Additionally, angular displacements may not detect certain translation-type movements, such as when a participant's head pokes forward, where the relative inclination of the head and torso does not change. This H-N motion would present detectable linear accelerations, despite no measurable change in angular orientation. In spite of these findings, only a few labs have examined this parameter in prehospital literature[21,23,84].

A suitable alternative to video-based systems for ambulance transport are inertial measurement units (IMUs) which consist of a miniature accelerometer and/or gyroscope[86]. Combined with a magnetometer, they record data with 9 degrees of freedom. These devices can accurately quantify both the orientation and acceleration of body segments (e.g. head/neck) without requiring a clear line of sight. This method is reliable, as acceleration is directly measured, and not inferred via differentiation[87]. IMUs also present the advantages of being compact (and therefore suitable to a limited experimental space), accurate, and provide measures of both acceleration and orientation. One popular IMU is the XSens MTw, which has been successfully used to quantify head kinematics[88] and also provides the benefits of simplicity, low power consumption, and good stability over a wide range of temperatures[86]. However, despite these apparent benefits over other techniques, IMUs have seen only limited use in SI. A recent study has developed a novel method of IMU-based assessment of motion during full and collar-only SI, which has demonstrated excellent validity relative to existing techniques[23]. These features make IMUs an ideal approach to quantifying patient H-N motion within the confines of an actual vehicle.

Transport

The process of transport to a primary care facility and subsequent in-hospital triage represent the largest proportion of time patients spend immobilized (i.e. in SI)[66]. Surprisingly, the vast majority of studies on spinal precautions have been restricted to extrication and boarding[35,89,90,91]. Within the Winnipeg region, the transport and triage period represents ~82% of the total immobilization time, and is on average 80 minutes[92]. However, durations as long as 7 hours are not unusual (e.g. rural patient)[66].

Although the effectiveness of SI is debated and mechanism of secondary injury difficult to ascertain, authors have suggested neurological deterioration may occur during transport. Toscano found that 28.1% of cases exhibited neurological deterioration during ambulance staff assessment and transport[2]. The possibility of worsening a patient's condition is important enough to warrant further investigation and identify specific mechanisms or time-periods where the risk of secondary injury is greatest.

During ambulance transfer, H-N motion can be categorized as either voluntary (patient movement) or involuntary (inappropriate handling or vehicle motion). Involuntary H-N motion due to vehicle motion is likely the largest contributor to transport-related motion and may arise due to either driving tasks or road surfaces. During either circumstance, the vehicle and its occupants will be subjected to three main types of acceleration, which will expose the passengers to increased forces and/or displacements. First, passengers may experience linear accelerations in the direction of travel during tasks such as stopping at a traffic light, accelerating from a stopped position, or while passing other vehicles. The American Association of State Highway and Transportation Officials (AASHTO) has quantified typical deceleration rates for passenger vehicles at 3.4 m/s^2 [93]. These values could conceivably be much greater during 'emergency braking' scenarios. While ambulance-specific data is sparse, the literature states that ambulances must be able to maintain a sustained speed of 105 km/hr and should be able to produce acceleration from 0 to 88 km/hr in 25s"[94], which would correspond to an average acceleration of 1m/s^2. These numbers were echoed in a 2008 publication by the US General Services Administration (GSA)[95]. For patients in the supine position, these accelerations would act in the superior-inferior direction and potentially contribute to compression/distraction of the cervical spine and/or head flexion/extension (particularly if semi-reclined).

In contrast, the vehicle will experience centripetal (laterally-directed) accelerations while turning. For example, during turns performed at 50km/hr (radius=50m), theoretical values for centripetal accelerations of passenger cars are ~3.6 m/s^2. These tasks and accelerations will potentially induce H-N motion in the frontal or transverse planes (i.e. lateral flexion and/or rotation). Lastly, variation in road surfaces, such as poor road conditions or traffic calming devices (speed bumps) will induce accelerations in the vertical plane and contribute to neck flexion/extension. The effects of road surfaces on ambulances have been investigated by Alberti, who reported average acceleration (RMS) measures of $1 m/s^2$ for city driving, and $1.9 m/s^2$ over rural roadways[96]. Unfortunately, no measures of neck kinematics supplement this data, nor is the ambulance acceleration specific to any driving tasks or speeds (only road types). In other reports, bumps on the road have been measured as high as $19.6 m/s^2$ [97] , but likely occur at much greater frequencies than centripetal accelerations. The next logical step is to determine how these typical accelerations, as well as less-frequent 'emergency' accelerations, would impact the H-N motion of ambulance patients.

Only a small number of studies have evaluated involuntary head/neck in the context of spinal precautions during ambulance transport. In a laboratory setting, Perry et al. secured participants to a backboard that was affixed to a dynamic platform, intended to simulate vehicle motion[21]. In spite of the use of full SI, the authors reported increased axial rotation and lateral flexion related to vehicle motion, with an average displacement of 8^o. The levels of H-N motion were judged by a panel of three experienced neurologists and neurosurgeons to be "clinically significant" with regards to the potential contribution to spinal cord injury[21]. Interestingly, that magnitude of angular displacement is equivalent to that observed during maximal voluntary efforts in SI[98]. The major limitations of this study were the use of simulated rather than actual ambulance motion and a limited range of acceleration magnitudes (< 1.7 m/s2), which were assessed in the frontal/lateral plane only (i.e. neck lateral-flexion/rotation). A more recent study assessed the acceleration of the head and neck during transport on medical utility vehicles and found differences in the relative accelerations in the horizontal and vertical directions, suggesting that differences in surface-type and vehicle specifications (i.e. axle suspension systems) create horizontal and vertical perturbations that are conveyed to vehicle occupants[84]. However, the authors reported only linear acceleration and did not examine angular displacement. These studies provide preliminary evidence that substantial motion appears at the H-N despite the use of spinal precautions, however a comprehensive examination of transport-related H-N motion during spinal precautions remains to be performed.

Two studies have explicitly compared SI and SMR during transport. The first assessed differences between SI and SMR in terms of linear displacement of the head relative to the chest[22]. Their driving tasks consisted of left and right turns, starts and stops, reaching a maximum speed of 32 km/hr. The only kinematic variable reported was the lateral displacement of various body parts, using questionable methodology (swinging paper disks and lasers). Interestingly, the authors concluded a better ability of SMR to control lateral movement, compared to SI. Only one study has been conducted to assess the impact of real ambulance motion on head and neck kinematics using rigorous methodology and suitable equipment (IMUs)[99]. No differences were found between SI and SMR in the ability to reduce head exposure to angular displacement. Unfortunately, that work did not differentiate nor control for differences between driving tasks or driving speeds, greatly reducing the implications of their findings. The next logical step is to examine ambulance acceleration measures specific to common driving tasks, undertaken at a range of speeds, and to measure the corresponding motion at the H-N segment. This addresses a significant gap in the literature and would allow knowledge users to identify specific circumstances during transport where the risk for secondary injury may be elevated.

Conclusion

In conclusion, the devastating effects of spinal cord injuries are undeniable[100]. SI has been used to reduce the possibility of potentially harmful movement following the initial injury. While that paradigm is itself subject to controversies, attention must be given to the effectiveness of spinal precautions protocols, particularly the differences between full (SI) and partial procedures (SMR). Transport of spinal trauma victims, despite its inherent risks, has never been studied in the field. The purpose of this study is to characterize neck and ambulance kinematics during ambulance driving tasks and compare effect of different spinal precaution protocols.

Objectives

The study has 3 primary objectives:

Objective 1: Characterize ambulance accelerations participants are exposed to during different ambulance transport tasks.

Hypothesis: Ambulance acceleration will increase with speed and be greatest during sudden stops & speed bumps.

Objective 2: Quantify H-N motion (displacement and acceleration) experienced by patients during ambulance transport across different driving tasks and speeds.

Hypothesis 1: H-N motion will vary between driving tasks and be greatest during sudden stops & speed bumps.

Hypothesis 2: H-N motion will increase with speed.

Objective 3: Compare H-N kinematics between SI and SMR.

Hypothesis: SI will be more effective than SMR at reducing angular displacement and differential accelerations of the H-N segment.

Title Page

Manuscript: Head-neck kinematics and spinal precautions during ambulance transport tasks: effects of full spinal immobilization and spinal motion restriction

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Abstract

Introduction: The purpose of this study is to determine the influence of vehicle motion on head/neck (H-N) motion (displacement and acceleration) during ambulance transport and to compare the effectiveness of two spinal precautions (SP) protocols: spinal immobilization (SI) vs. spinal motion reduction (SMR). **Methods**: This is a balanced-order, repeated measures comparison of two spinal precaution conditions on H-N kinematics during a series of ambulance driving tasks. Healthy volunteers (n=18) underwent ambulance transport, consisting of various driving tasks and speeds, under two SP protocols. Inertial measurement units (IMUs) were placed on participants' heads and sternums, while two more IMUs were affixed to the backboard and stretcher mattress frame. Outcome measures included peak and average (RMS) acceleration values for all kinematics, as well as angular displacement of the H-N. Participants characteristics were also recorded. **Results**: Ambulance accelerations varied across driving tasks [2.5 – 9.5m/s^2] and speeds [3.0 – 6.2 m/s^2] and were associated with a wide range of H-N displacements [7.2 – 22.6°] and accelerations [1.4 – 10.9 m/s^2]. In a number of tasks, a small, but significant reduction in H-N motion was detected in SI versus SMR [<5°; <3.8 m/s^2], however some tasks (speed bumps, s-turns) revealed greater H-N motion in SI. **Conclusion**: This study suggests that ambulances expose their contents to a range of accelerations specific to driving tasks and speeds. For the majority of driving tasks and speeds, SI and SMR do not appear to differ greatly in their ability to restrict H-N motion. This work also reinforces the complementarity of multiple kinematic parameters, such as acceleration peaks, averages, and orientation peaks.

INTRODUCTION

Spinal precautions are a common aspect of prehospital emergency care[3]. They are undertaken to protect a potentially injured and unstable spine. Traditionally, all suspected neck injuries were treated with spinal immobilization (SI) – a protocol consisting of application of a rigid cervical collar and placement on a long rigid backboard with straps and head blocks[71]. Recently, this practice has been questioned, in part due to increasing evidence of the deleterious effects of SI, such as increased treatment time[72], delayed transport[50], pressure sores[75], respiratory difficulties[7,64], and discomfort eliciting movement in a conscious patient. Moreover, the effectiveness of SI at preventing secondary injuries has been questioned[10]. Consequently, in many jurisdictions, the use of a backboard has been restricted and many patients receive spinal precautions in the form of spinal motion restriction (SMR) protocols, usually consisting of a rigid collar and stretcher mattress[12,101].

The protection (motion restriction) provided by SMR has been compared to SI for various aspects of prehospital emergency care. For instance, during extrication, up to 26° of H-N motion were reported despite the presence of a cervical collar[15]. Studies on patient transfers from the ground onto a vacuum mattress also show similar amounts of H-N motion, up to 24°[102]. Subsequent studies have indicated a poor efficacy of SI appliances[103], a lack of differences between SI and SMR[104], or situations in which SMR surpasses the efficacy of SI[105]. Consequently, manual handling has been minimized during extrication and loading, and self-removal is encouraged when deemed safe[15]. In contrast, transport, which is one of the primary purposes of pre-hospital emergency care, accounting for up to ~82% of the total immobilization time[92], has seen only limited study. During transport, involuntary H-N motion due to vehicle activity is likely the largest contributor to transport-related motion and may arise due to either driving tasks or road surfaces.

One of the first studies to examine transport used simulated ambulance motion on a vibrating platform and found 'clinically significant' amounts of H-N motion (>7°) in SI, and little difference between various methods of securing the head to the backboard[21]. While this study provided some of the first estimates for the amount of H-N motion that may occur during transport, it was limited to accelerations in only one direction (lateral) and it is unclear to what extent the simulated motion is reflective of actual driving tasks. A small, proof-of-concept study using real ambulances revealed less H-N motion during SMR compared to SI[22], however this study quantified movement as only linear displacement, making comparisons to commonly reported angular orientation outcomes difficult. More recently, a study using more comprehensive outcomes showed no difference in cervical spine motion between SMR and SI during transport, and in some cases (transfer to stretcher), SMR resulted in less observed H-N motion[99]. While both studies provided evidence supporting SMR, in each case data were analyzed across an entire ambulance trip. Therefore, it is unknown if, or under which driving conditions, SI and SMR might yield different amounts of H-N motion restriction. Further, although some description of driving route was provided, the characteristics of ambulance kinematics were not reported[99], making it difficult to compare results across studies. In fact, a description of what vehicle motion (e.g. accelerations) patients are exposed to during transport is absent, in addition to how this might influence H-N motion.

The purpose of this study is to quantify H-N motion during a representative range of ambulance transport tasks and to compare the effects of SI and SMR. This information will further the understanding of the efficacy of spinal precautions and potential secondary injury mechanisms during prehospital emergency care of patients with suspected spine injuries.

METHODS

Study Design

This is a balanced-order, repeated measures comparison of two spinal precaution conditions (SI & SMR) on head-neck (H-N) kinematics during a series of ambulance driving tasks (ethical approval: #HE02975, University of Winnipeg REB).

Participants

A sample of convenience of healthy volunteers was recruited (n=18, male = 11; height = 171.5±7.0cm; mass = 73.0±13.3kg; neck circ. = 12.3±1.3 yrs; neck length = 14.2±1.8 cm). Exclusion criteria included recent injury (< 6 months), previous history of major trauma, and/or known impairments to the range of motion/strength of the head/neck/trunk regions. Neck length (sternal notch to mandible) and circumference (widest) were measured using an anthropometer (Lafayette Instrument Company, Lafayette, USA) and cloth tape, respectively.

Protocol

The study was conducted in a large, paved space (180 x 120 meters), closed to outside traffic, and with good surface quality. After providing informed consent, participants received two types of spinal precautions: spinal immobilization (SI), consisting of a rigid backboard (Pro-lite Pine Board, Rapid Deployment Products; Ivyland, Pennsylvania USA) and cervical collar (Ambu Perfit ACE, Ambu, Inc.; Ballerup, Denmark); spinal motion restriction (SMR), consisting of a cervical collar only. Immobilization appliances were fitted to existing practice standards by an Intermediate Care Paramedic with nine years of emergency medicine experience.

Following application of spinal precautions, participants were placed on a stretcher mattress in the back of an ambulance and transported through a series of driving tasks at various speeds, consisting of: accelerating; single-turn; decelerating (performed following the single-turn); s-turns (repetitive turns); speed bumps (traffic calming); abrupt starts; abrupt stops (Table 1). The driving tasks were dynamic (i.e. involved some form of acceleration) and selected to reflect a range of manoeuvres encountered during ambulance transport, as well as different acceleration directions (e.g. vertical, centripetal/lateral). The single turn was modeled after a typical urban, right-turn merge lane and the abrupt start/stops reflected a rapid application of brakes at low speed (e.g. to avoid a pedestrian). One repetition of each task and speed combination was performed, with the exception of abrupt starts/stops and speed bumps (n=2, maximum reported). Appropriate fit/adjustment of spinal appliances was confirmed between each driving task. Each series of tasks lasted approximately 30 minutes; following a break (5 mins) the tasks were repeated for the remaining condition (SI or SMR, balanced-order). Trials were conducted using active fleet ambulances (Ford F350 and Chevy Crestline; mean mileage: 195,706 km) from a large urban centre (Winnipeg, Manitoba, Canada) and were driven by active duty paramedics with > 2 years experience.

Table 1. Description of driving tasks and speeds. Tasks were performed in the order depicted and repeated for SI and SMR in balanced order.

Task	Speed (km/hr)	Description	Acc direction (source)
accelerating	15, 25, 35, 45	Speeding up to target speed in 40 metres.	longitudinal (engine)
single turn	15, 25, 35, 45	Single right-hand corner (90°), radius: 30m.	lateral (centripetal)
decelerating	15, 25, 35, 45	Slowing down to target speed in 20 meters.	longitudinal (brakes)
s-turns	15, 25, 35	Alternating right & left ‘weaving’ turns, spacing: 10m	lateral (centripetal)
abrupt starts	5	Low-speed, high acceleration speeding up	longitudinal (engine)
abrupt stops	5	Low-speed, high deceleration slowing down	longitudinal (brakes)
speed bumps	5	Traversing traffic-calming speed bumps at low speed	vertical (road surface)

Outcomes and Measurements

Head-neck (H-N) kinematics (angular displacement, linear acceleration) were acquired using two miniature, wireless inertial measurement units (IMUs) (XSens MTw; internal sampling rate: 1000Hz; range: ±16g; size: 47 x 30 x 13mm) attached to the anterior forehead (glabella) and superior sternum (distal to cervical collar) with double-sided, hypoallergenic tape. Ambulance kinematics were obtained from a third sensor affixed to the stretcher frame. Sensors were aligned such that the x-, y-, and z-axes corresponded to the lateral, anterior-posterior, and superior-inferior directions, respectively. Data from all three sensors was time-synchronized, down-sampled (75Hz), low-pass filtered (5 Hz) and transmitted wirelessly to a laptop computer (Dell, Windows 8) using manufacturer software (MtManager 4.3). H-N angular displacement was computed as the difference between the flexion-extension (roll), rotation (pitch) and lateral-flexion (yaw) angles of the head and sternum sensors, corrected to the start of each task. The peak (max) for each plane and total displacement (sum of peaks) were extracted. The accelerometer anterior-posterior (z) and superior-inferior (y) axes were aligned with the respective axes of the head using a rotation matrix. H-N linear acceleration was computed as the resultant acceleration of the differences between the head and sternum accelerations at each axis:

resultant acceleration = square root $[(head_x – sternum_x)^2 + (head_y\text{-}sternum_y)^2 + (head_z\text{-}sternum_z)^2]$

The peak and root mean square (RMS) of the H-N linear acceleration were extracted for each task, as well as the peak (max of absolute values) of each axis and total (sum of peaks). Ambulance acceleration was estimated as the resultant (peak, RMS) of the 3-axes in the stretcher sensor. Following each spinal precaution condition, participants reported region-specific comfort (head, neck, trunk, legs) using a 10cm visual analogue scale (0 = extreme discomfort, 10 = very comfortable), as well the extent comfort changed during the trial (-5 = worsened a lot; 0 = no change; 5 = improved a lot).

Analysis

The effects of driving task, speed, and spinal precautions condition on H-N motion (angular displacement, linear acceleration) and ambulance (linear acceleration) kinematics were tested using a linear mixed-model, with post hoc comparisons carried out for significant main effects (one-sided for tests of SI < SMR). Descriptive statistics are reported as mean±standard error and estimates of effect sizes are provided using 95%CIs. The relationship between outcomes was tested using Pearson correlation and linear regression models were used to identify significant predictors of H-N motion. Significance was set at $\alpha = 0.05$. Statistical analysis was performed on SPSS 19 (IBM Corp.; Armonk, New York USA).

RESULTS

Ambulance Kinematics

Ambulance acceleration (peak) differed across driving tasks ($F(5,68)=188.9$, $p<.001$) and speeds ($F(3,115)=135.0$, $p<.001$), but not spinal precautions condition ($p>.89$). Acceleration differed between all tasks ($p>.53$), with the exception of accelerating and abrupt starts ($p>.53$) (Table 2, Task). Ambulance acceleration also differed across all speeds (+1.04±0.2 m/s^2, $p<.01$) (+27±5%), with the exception of 5 km/hr and 45 km/hr ($p>.81$) (Table 1, Speed). Post hoc tests by task revealed differences in acceleration (peak) across speeds ($p<.05$) during accelerating (15 km/hr:1.7±0.2m/s^2; 25 km/hr:2.0±0.3 m/s^2; 35 km/hr: 2.7±0.3m/s^2; 45 km/hr: 2.5±0.3m/s^2); braking (2.3±0.2m/s^2; 3.7±0.3m/s^2; 5.0±0.3m/s^2; 6.1±0.4m/s^2); turning (4.3±0.3m/s^2; 6.6±0.3m/s^2; 7.2±0.4m/s^2; 8.4±0.4m/s^2) and s-turns (2.9±0.3m/s^2; 3.7±0.3m/s^2; 4.7±0.4m/s^2)($p<.05$). Similar effects were apparent for the average (RMS) acceleration, which was 49.4±0.5% of peak values (see Appendix 1).

Table 2. Main effects of driving task and speed on ambulance acceleration (peak) during controlled driving tasks performed at 5 - 45 km/hr. Dashed lines indicate significant differences between tasks and speeds. M [95%CI] shown.

	acceleration, peak (m/s^2)
Task+	
speed bump	9.52 [7.89, 11.1]
turn	6.76 [6.50, 7.02]
abrupt stop	6.07 [5.67, 6.78]
s-turn	4.88 [4.56, 5.20]
decelerating	4.28 [4.05, 4.51]
abrupt start	3.00 [2.70, 3.30]
accelerating	2.52 [2.35, 2.68]
Speed (km/hr)+	
5	6.20 [5.60, 6.79]
45	6.11 [5.78, 6.45]
35	5.26 [5.00, 5.52]
25	4.37 [4.16, 4.58]
15	3.00 [2.82, 3.18]

+main effect, $p<.05$

Head-neck Angular Displacement

H-N angular displacement differed across driving tasks (F(5, 76.4) = 104.5), $p < .001$), speeds (F(3, 67.3) = 22.5), $p < .001$) (Table 2), and spinal precautions (F(1,153.7) = 173.0, $p < .001$). Collapsed across speeds, the greatest displacements occurred during turning and s-turning (21.6±0.9º, p<.01), however the differences relative to slowing, abrupt stops, and speed bumps were small (-3.8±1.3º; -17.6±6%; $p < .01$), with the lowest displacements during abrupt starts and accelerating (-13.4±1.2° vs turns) (-62±5.6%) (Table 3, SI & SMR). Displacement increased an average of 3.2±1.4º (+23±10%) between each of 15, 25 and 35 km/hr speeds (p<.01) and was not different between the 5 and 25 km/hr (p>.36) or 35 and 45 km/hr conditions (p>.67) (Table 3, Speed). The overall effect of spinal precautions condition was relatively modest, with 2.9° [1.6, 4.2] (25±5.7%) more H-N motion in SMR. Comparisons by task revealed less H-N motion in SI during speed bumps (-6.7±2.2º; -32.4±10.6%), turning (-4.8±1.9º; -21±8.3%) and accelerating (-1.9±0.6°; -23.5±7.4%), with trends during decelerating (-2.3±1.4º; -12±7.3%) and abrupt starts (-2.8±1.5º;-27±14.5%), but not abrupt stops or s-turns (Table 3; SI, SMR).

Table 3. Main effects of driving task and speed on neck displacement in patients receiving spinal precautions during controlled ambulance transport tasks. Dashed lines indicate sig dif between tasks for SI & SMR comparisons (p<.05). M [95%CI] shown.

	H-N displacement, total (°)			
Task+	**SI & SMR**	**SI**	**SMR**	**sig. (p)**
s-turn	22.6 [20.6, 24.5]	21.4 [18.1, 24.7]	23.7 [21.7, 25.8]	>.12
turn*	20.5 [18.6, 22.4]	18.1 [15.1, 21.1]	22.8 [20.3, 25.4]	<.01
decelerating	18.0 [16.6, 19.4]	16.9 [14.8, 18.9]	19.2 [17.2, 21.2]	>.06
abrupt stop	17.8 [15.0, 20.5]	18.2 [13.9, 22.5]	17.3 [13.6, 21.0]	>.38
speed bump*	17.3 [15.4, 19.6]	14.0 [10.7, 17.3]	20.7 [17.2, 24.2]	<.01
abrupt start	9.1 [7.2, 10.9]	7.7 [5.4, 9.9]	10.4 [7.3, 13.6]	>.08
accelerating*	7.2 [6.6, 7.7]	6.2 [5.4, 7.0]	8.1 [7.3, 9.0]	<.001
Speed+				
5*	14.7 [13.4, 16.0]	13.5 [11.4, 15.1]	16.2 [14.3, 18.0]	<.05
15*	12.9 [11.8, 13.9]	11.3 [10.0, 12.6]	14.5 [12.8, 16.2]	<.01
25*	15.9 [15.0, 16.9]	14.9 [13.4, 16.3]	17.0 [15.7, 18.3]	<.05
35	19.5 [17.9, 21.0]	18.4 [15.8, 21.0]	20.6 [18.8, 22.3]	>.08
45*	19.0 [16.5, 21.5]	16.9 [12.8, 20.9]	21.2 [17.8, 24.5]	<.05

+main effect, p<.05; *effect of SI, p<.05

Post hoc tests revealed significantly less displacement in SI for nearly all speeds during accelerating and turning, but not stopping or s-turns, with the greatest difference occurring while turning at 45 km/hr (-10.8±2.6°; -32±8%)(Figure 2), which exceeded the difference during speed bumps (-6.7±1.4°; -32±7%). The reduction in H-N motion under SI could be attributed almost entirely to a reduction in rotation, rather than lateral flexion or flexion/extension (Figure 2, data table) – a finding also apparent during speed bumps (-5.8±1.4°) and abrupt starts (-2.0±0.5°) (not shown). Interestingly, during s-turns there was *increased* lateral flexion in SI at the two highest speeds ($p<.05$), which may explain the absence of a difference in total displacement. Lastly, the effect of speed was most pronounced during turning ($p<.05$) and s-turns ($p<.01$) where significant increases in displacement were detected between all speeds, whereas during accelerating and decelerating only the 45 and 25 km/hr speeds differed from the other speeds, respectively ($p<.05$).

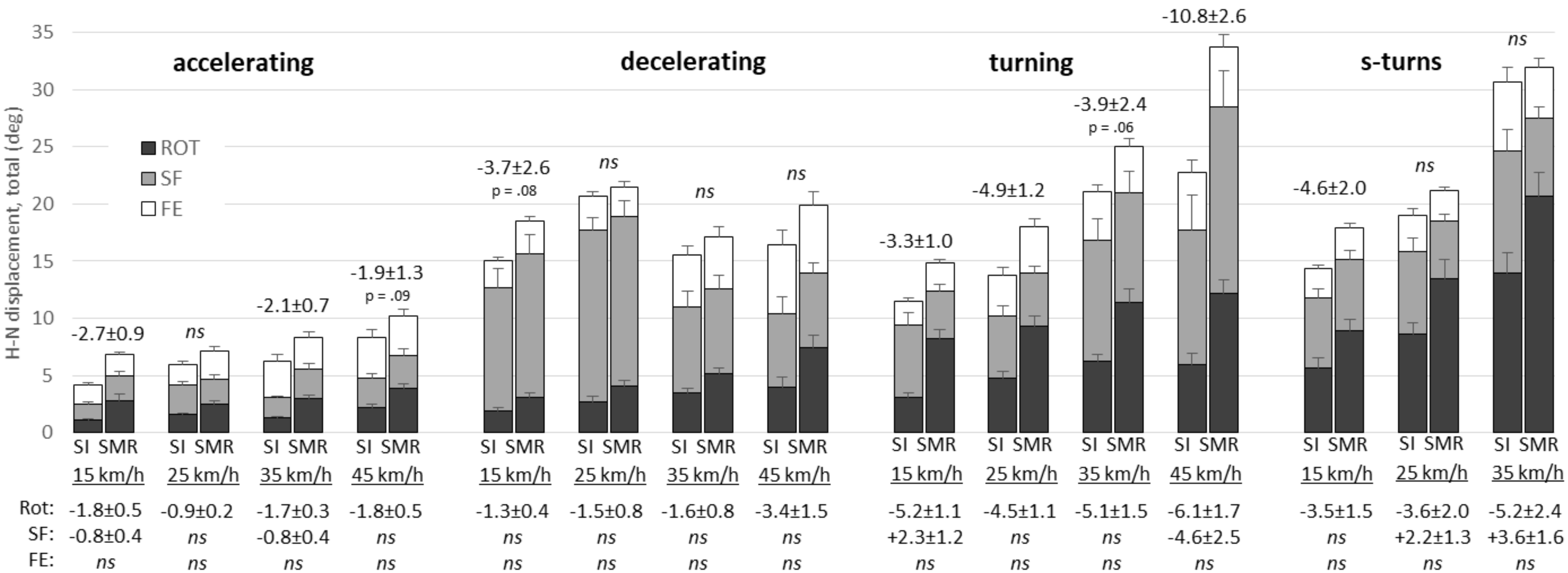


Figure 1. Effect of spinal precautions condition (SI vs SMR) on head-neck displacement during accelerating, decelerating, turning and s-turns tasks performed at 15, 25, 35 and 45 km/hr. Data labels (above bars) indicates difference in total displacement. Data table (below bars) indicates differences in rotation (ROT), lateral flexion (SF), and flexion-extension (FE). M±SE shown. p<.05. ns: not significant.*

Head-neck Linear Acceleration

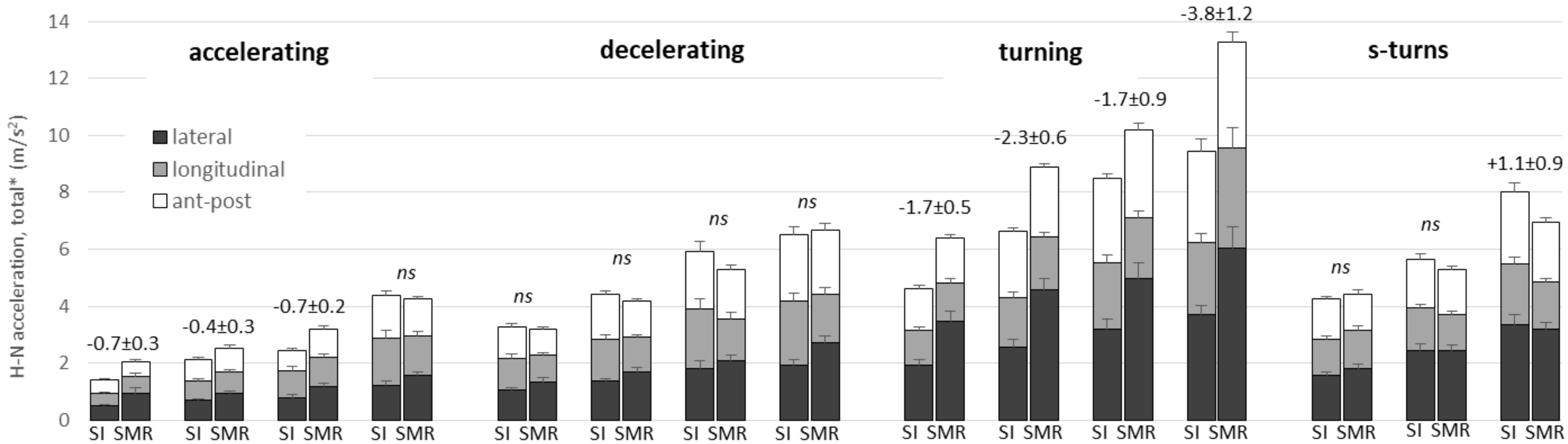
H-N acceleration (peak) differed across driving tasks ($F(5, 52.5) = 101.1$, $p<0.001$) and speeds ($F(3, 69.1 = 57.6$, $p<.001$), while the effect of spinal precautions varied across tasks ($F(5,52.5) = 6.67$, $p < .001$). Collapsed across speeds, the greatest H-N accelerations occurred during speed bumps, which were substantially greater than turns and abrupt stops ($+6.35\pm0.61 m/s^2$; $+139\pm13\%$), as well as the remainder of the tasks ($+8.73\pm0.04 m/s^2$; $+400\pm2\%$) (Table 4, SI & SMR). Comparisons by task revealed less acceleration in SI during turning ($-1.73\pm0.30 m/s^2$), a trend during accelerating ($-0.19\pm0.12 m/s^2$), and more acceleration in SI during abrupt stops ($2.54\pm1.23 m/s^2$) and abrupt starts ($1.09\pm0.51 m/s^2$) (Table 4, SI, SMR). No difference was detected during speed bumps ($p>.31$), s-turns ($p>.38$) and slowing down ($p>.30$).

Table 4. Main effects of driving task and speed on neck acceleration (peak) in patients receiving spinal precautions during controlled ambulance transport tasks. Dashed lines indicate significant differences between tasks for SI & SMR comparisons (p<.05). M [95%CI] shown.

	H-N acceleration (m/s^2)			
Task+	**SI & SMR**	**SI**	**SMR**	**p**
speed bump	10.91 [7.04, 14.78]	10.00 [4.50, 15.55]	11.84 [5.92, 17.75]	>.31
abrupt stop*	4.66 [3.38, 5.94]	5.93 [3.56, 8.29]	3.39 [2.24, 4.54]	<.05
turn*	4.46 [4.16, 4.76]	3.59 [3.28, 3.91]	5.32 [4.80, 5.80]	<.001
s-turn	2.91 [2.69, 3.13]	2.94 [2.57, 3.32]	2.87 [2.63, 3.12]	>.38
decelerating	2.37 [2.19, 2.54]	2.41 [2.13, 2.69]	2.32 [2.11, 2.54]	>.30
abrupt start*	2.03 [1.50, 2.57]	2.58 [1.54, 3.62]	1.49 [1.17, 1.80]	<.05
accelerating	1.38 [1.26, 1.50]	1.28 [1.11, 1.46]	1.47 [1.31, 1.64]	>.06
Speed+				
5	5.87 [4.51, 7.22]	6.16 [4.19, 8.14]	5.57 [3.57, 7.57]	>.33
45*	3.69 [3.35, 4.03]	3.29 [2.89, 3.70]	4.09 [3.52, 4.67]	<.05
35	3.22 [2.98, 3.46]	3.07 [2.72, 3.42]	3.36 [3.05, 3.67]	>.17
25*	2.51 [2.36, 2.66]	2.31 [2.10, 2.54]	2.72 [2.50, 2.93]	<.05
15*	1.89 [1.74, 2.02]	1.61 [1.47, 1.74]	2.16 [1.91, 2.40]	<.05

+main effect, p<.05; effect of SI, p<.05

Post hoc tests revealed a similar pattern as displacement, with less acceleration in SI for nearly all speeds during accelerating and turning, but not stopping or s-turns (greatest difference: -3.8±1.2m/s^2, turning 45 km/hr)(Figure 2). Similarly, the reduction in linear acceleration could be attributed largely to less lateral H-N acceleration, rather than longitudinal or anterior-posterior (Figure 2, data table) (speed bumps: -2.4±0.6m/s^2, not shown). In contrast, the increased H-N acceleration in SI during abrupt stops and starts was due to accelerations in the anterior-posterior (stop: +1.8±0.8m/s^2; start: +0.8±0.4m/s^2) and longitudinal (stop: +2.0±1.1m/s^2; start: +0.9±0.5m/s^2) directions (lateral: $p>.45$). Increased longitudinal accelerations in SI were also detected at several high speed accelerations/decerations. Significant increases across speeds were detected for all conditions ($p<.05$). H-N acceleration (RMS) was 30.5±0.5% of peak values across all conditions (see Appendix 1, Crest Factor), with significant differences between SI and SMR at most speeds during accelerating (-0.1±0.04m/s^2), turning (-0.36±0.06m/s^2), s-turns (-0.31±0.08m/s^2) and abrupt starts (+0.28±0.14m/s^2) (see Appendix 1, RMS).



	15 km/h	25 km/h	35 km/h	45 km/h	15 km/h	25 km/h	35 km/h	45 km/h	15 km/h	25 km/h	35 km/h	45 km/h	15 km/h	25 km/h	35 km/h
Lat:	-0.5±0.2	-0.2±0.1	-0.4±0.1	-0.3±0.2	-0.3±0.2	-0.3±0.2	*ns*	-0.8±0.2	-1.4±0.4	-2.0±0.5	-1.8±0.7	-2.4±0.8	-0.3±0.2	*ns*	*ns*
Long:	-0.2±0.1	*ns*	*ns*	+0.3±0.2	*ns*	*ns*	+0.7±0.3	+0.5±0.2	*ns*	*ns*	*ns*	-0.9±0.6	*ns*	+0.2±0.1	+0.4±0.3
A-P:	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	-0.6±0.4	*ns*	*ns*	+0.5±0.3

*Figure 2. Effect of spinal precautions condition (SI vs SMR) on head-neck acceleration during accelerating, decelerating, turning and s-turn tasks performed at 15, 25, 35 and 45 km/hr. Data labels (above bars) indicates difference in total displacement. Data table (below bars) indicates difference (M±SE) between SI and SMR for each direction. *note: total H-N acceleration (sum of 3 axes) was near perfectly related to the peak of the resultant acceleration (r=0.99), with double the magnitude (2.02±0.03x).*

Comfort and relationship between measures

During SI participants reported lower comfort for the head (SI: 3.9±0.5, SMR: 5.5±0.5, $p<.001$), trunk (SI: 5.24±0.5, SMR: 6.64±0.4, $p<.01$), and legs (SI: 5.6±0.5, SMR: 8.3±0.3, $p< .001$), but not neck (SI: 5.2±0.5, SMR: 5.0±0.5, $p>.24$). Participants perceived comfort worsening over time during SI (-2.4±0.3, $p<.01$) and improving marginally in SMR (+0.7±0.3, $p<.05$). Low to moderate relationships were found between ambulance kinematics (acceleration, speed) and H-N motion ($0.22 < r < 0.68$, $p<.001$), but not participant characteristics and H-N motion ($-0.07 < r < .02$, $p> .19$), aside from a weak relationship between neck length and H-N displacement ($r = -0.14$, $p<.01$). A linear regression model using significant predictors (ambulance acceleration, speed, neck length) accounted for 24.6% of the variation in H-N displacement, which improved to 45.6% with the inclusion of spinal precaution condition and driving tasks as predictors. By contrast, ambulance kinematics along (acceleration, speed) accounted for 50.0% of the variation in H-N acceleration, and was improved only slightly by including driving tasks and spinal precautions condition to 55.4% (See Appendix 1).

Table 5. Relationship between ambulance kinematics, individual characteristics and head motion (acceleration, displacement)

	H-N displ, total	H-N acc, peak
ambulance kinematics		
acceleration, peak	r = 0.42, p<.001	r = 0.68, p<.001
acceleration, rms	r = 0.41, p<.001	r = 0.49, p<.001
speed, average	r = 0.22, p<.001	r = -0.11, p<.05
individual characteristics		
mass	r = -0.06, p>.19	r = 0.01, p>.93
BMI	r = 0.02, p>.69	r = 0.01, p>.98
neck length	r = -0.14, p<.01	r = 0.01, p>.85
height	r = -0.07 p>.08	r = -0.01 p>.93

H-N displ & H-N acc: $r = 0.31$, $p<.001$

DISCUSSION

This study addresses a significant gap in the understanding of spinal precautions in emergency care by providing estimates for H-N motion during specific ambulance transport tasks, across two spinal precautions conditions. Consistent with preliminary findings from other studies, these results demonstrate substantial H-N movement can occur during transport despite the use of spinal precautions (> 17° across most tasks)[21,22,84,99]. Relative to other prehospital tasks, the total displacements here are greater than those measured during extrication (~10°)[14,89], and patient transfers (~11°)[90], but less than that reported during maximal voluntary struggles (~95°)[23]. They also add to the data questioning the benefit of SI – both on findings of relatively small differences between conditions, but also in scenarios where H-N motion in SI was greater than SMR and differences in perceived comfort.

These results extend previous work by providing driving task-specific estimates and identifying circumstances where H-N motion may be particularly large. While substantial H-N motion may be expected during high-speed, turning-style maneuvers (>30°), considerable mobility also occurred during low-speed (high-acceleration) tasks, such as speed bumps and abrupt start and stops. This is important because unlike high speed turns, these may be unavoidable driving tasks (e.g. traffic calming, road hazards). Amongst tasks exceeding 17° of displacement, the differences were comparatively small (~ 5°) in spite of a fairly large range of ambulance accelerations (4-9 m/s^2), suggesting that while relatively little acceleration is required to induce some H-N motion, substantial additional acceleration is required to further increase displacement. In that regard, SI appliances can be regarded as effective at limiting H-N motion to some degree. On a per-axis basis, our values are comparable to those reported by Perry using simulated transport (8°)[21], but are smaller in magnitude than Swartz (up to 18°)[99]. This may reflect a difference in task duration (<30 seconds studied here vs 15-minute drive) where the effects of multiple exposures accumulated (e.g. causing SI appliances to loosen) and/or accelerations characteristics differed (Swartz reached speeds of 84 km/hr). Regardless of task/outcome, H-N displacement in studies examining transport[22,99], as well as many other aspects of pre-hospital care[66,102,106,107], exceed 8°[21], putting into question this threshold's clinical significance. Lastly, in this study, most of the displacement was observed as rotation and lateral-flexion, more so than flexion-extension (likely due to supine positioning). This suggests spinal precautions are least effective at limiting H-N motion in the frontal and transverse planes. It is unknown whether motion in any one axis is more deleterious than another, or if some other aspect of head kinematics may be harmful[108]. Future studies are required to correlate kinematics with changes in outcomes.

A primary assumption of SI (backboard use) is that it will reduce H-N motion of the potentially injured spine. While this is the first study to reveal systematic differences (reductions) in H-N motion due to SI use during transport, the overall effect size is very small (<5°). Taken across all tasks, these results seem to question the benefit of SI, and support those of Swartz, who did not find any difference between SI and SMR during transport[99]. In contrast, by comparing across a wider range of tasks, it was possible to identify circumstances where differences were larger (speed bumps and high-speed turns), and so it is possible the benefit (if any) of SI would not be apparent until exposed to large perturbations. Therefore, while it is reasonable to conclude backboard use provides comparatively little additional protective effect across most tasks encountered, it is challenging to extrapolate to what might happen in the (likely rarer) circumstances of high outside perturbations (where perhaps secondary injuries are more likely to occur). For these tasks, whether the additional H-N motion experienced by SMR on top of the already large displacements would result in injury is not known. Independent of the magnitude of difference, these results add to the evidence on mechanisms of SI protection – that is, a primary reduction in rotation (or frontal plane) motion, an effect that can most likely be attributed to the head blocks. Given no difference in flexion-extension, it seems the straps used to secure the head to the backboard provide little additional protection beyond the collar during transport, although this should be tested specifically.

One significant finding in support of SMR (over SI) were the circumstances where H-N motion in SI was greater than in SMR. In this study, this was best illustrated in the linear driving tasks (sudden starts & stops), where SI exceeded SMR for longitudinal acceleration, representing axial loading to the injured spine. This type of axial loading might be harmful and requires further scrutiny, as it replicates a known injury mechanism[10,109]. More H-N motion in SI was also apparent in some of the angular displacement measures, namely during sequential turns at higher speeds. In this case, differences were likely due to features of the spinal precaution devices, in this case the low-friction surface of the backboard, supporting the notion that patients slide on the backboard under high accelerations[21]. Other studies have also found greater H-N motion in SI, however this is generally attributed to differences in the manual handling of patients between SI and SMR protocols, rather than to the devices themselves[107,110]. This has encouraged a shift towards limiting the manual handling of patients, by inciting self-extrication when possible[13], for example. Our results suggest that perhaps a redesigned or alternate backboard is needed for patients still requiring SI. For instance, a vacuum mattress has been shown to reduce sliding[38,78,111]. These changes may also have the benefit of improving patient comfort, as not surprisingly, the hard, low-friction backboard (and corresponding straps) was found to adversely effect participants comfort in this study.

Investigating acceleration parameters of the neck was a novel aspect of this study. While acceleration has been used extensively to characterize vehicle dynamics[112,113] and in other areas of human movement research[114], it is still relatively new in spinal precaution research[23,84,99]. The single-axis H-N accelerations during transport in this study (up to 6 m/s^2) compare to those of voluntary motion (~6 m/s^2)[23] but are smaller than those found in other transport studies (~ 18 m/s^2)[84], indicating a potential difference in vehicle acceleration exposure (not quantified in the latter study) or differences in study methodologies. Nonetheless, this study suggests that significant amounts of acceleration can occur during transport, despite the use of spinal precautions. While for the most part, the effect of driving task and spinal precautions condition were similar between angular displacement and linear acceleration, it is clear acceleration and angular displacement are different constructs and not merely interchangeable. For example, while orientation provides a measure of the degree to which the head and neck deviate from an assumed safe position, acceleration provides some insight into the forces acting on the immobilized segments. Further, the relationship between acceleration and displacement across all tasks was $r = 0.31$, indicating a modest correlation between the two variables. This led to certain differences emerging in orientation, while others were only significant in acceleration. Secondary injury may not only be related to angular motion of the neck, but perhaps also to the forces acting across injured segments[108]. In addition to providing more detail about the kinematics of injured spine, the inclusion of acceleration in future studies provides other benefits such as easily processed, robust measure, low-power, non-intrusive devices[23].

Finally, this study provides initial estimates for the acceleration exposures of patients (and personnel) during specific ambulance transport tasks. The highest values (nearing 1g) were observed during high speed turns, abrupt stops and speed bumps – the latter conditions are particularly notable as they are low-speed conditions, indicating that high velocities are not a requisite condition for high acceleration exposures during ambulance transport (although in general, higher speeds resulted in higher accelerations during the remaining tasks). Most acceleration estimates encountered here exceeded those reported by Alberti in one of the few other studies to examine urban ambulance transport (RMS = $1 m/s^2$ urban)[96], however this may again be due to differences in experimental tasks/outcomes (i.e. average acceleration across an entire transport period vs short duration, task-specific accelerations reported here). In fact, apart from the accelerating conditions and low-speed braking/turning tasks, the exposures in this study exceeded the threshold for 'safe and reasonable' deceleration ($3.4 m/s^2$) proposed by AASHTO[93], as well as the vast majority (98%) of typical driving tasks for passenger vehicles ($2 m/s^2$)[115]. In these cases, vehicle type may play some role in these differences, as ambulances may experience greater accelerations during equivalent driving tasks due to vehicle characteristics (mass, suspension, drivetrain) and even patient/sensor location (over the rear axle of the vehicle in this study). The values from this study can assist the design of simulated ambulance transport studies, which to date have had to relied upon values published for passenger vehicles ($1.7 m/s^2$)[21]. Beyond the effect on H-N motion, acceleration exposure may be relevant during other aspects of pre-hospital emergency care. For instance, it may impact the ability of healthcare practitioners to deliver care – a concern raised by paramedic unions[92]. Understanding to what extent the driving tasks studied herein are encountered during actual ambulance transport (i.e. an entire trip) may provide further insight into these differences. The influence on ambulance acceleration on worker and patients beyond SI requires further study.

This study presented a few limitations. By using healthy volunteers, the extent to which these results reflect actual patients is not clear (e.g. unconsciousness, intoxication, muscle guarding, pain, combativeness, etc). It is possible that our small sample or variation led to some results being underpowered, however in the case of SI and SMR comparisons, most effect sizes with clinical significance should be comparatively large. Since it is difficult to blind drivers to conditions, it is possible their driving was influenced by the type of spinal precaution, although we detected no differences when analyzing ambulance acceleration data. It was somewhat surprising to find that ambulance acceleration (peak) was not strongly related to the H-N angular displacement. This could be due to the complex dynamics of both the ambulance-stretcher system, encouraging future studies to examine other parameters of ambulance acceleration (e.g. tasks specific integrals, or crest factors).

CONCLUSIONS

In conclusion, this study provides evidence suggesting SMR is at least equivalent to SI in reducing H-N motion in healthy volunteers, for most typical ambulance driving tasks. Since there are still no known safe thresholds for neck acceleration or displacement, it seems prudent that some degree of spinal precautions should still be undertaken. The decision as to when and how to immobilize a patient is complex and these results may assist in decision to consider SMR in jurisdictions where that has not yet been done. Examining multiple characteristics of neck kinematics has proven to be enlightening, as complimentary information emerged from each outcome measure.

SYNTHESIS DISCUSSION

The objectives of this study were to characterize acceleration exposure of patients during different ambulance transport tasks, characterize H-N motion during different driving tasks, and to compare SI to SMR. Emergency transport is a considerable component of pre-hospital care[116] and this study is the first to measure angular displacement and acceleration of the head and sternum concurrently, in an actual ambulance. Contributions to the literature include quantification of ambulance driving parameters and H-N kinematics, specific to various driving tasks and speeds. Beyond the discussion above, the results may have broader implications for prehospital management of suspected spine injuries, namely influencing emergency personnel's approaches to driving, and further encouraging a reconsideration of current spinal precaution approaches.

Implications for driving

This study brought to light varying transport-related determinants of H-N motion, which can broadly be categorized as modifiable or unmodifiable. Modifiable factors are those that could be controlled by ambulance personnel, for instance, by changing driving behaviour. For example, although velocity and acceleration are distinct, there are situations when velocity will be a determinant of ambulance acceleration, such as during turns at constant speeds. In these cases, reducing driving velocity when turning seems to be a reasonable recommendation. Based on the results of this study, reducing this centripetal acceleration would not only diminish H-N motion overall (orientation and acceleration), but also reduce the difference between SI and SMR. In other cases, certain driving tasks expose patients to high acceleration, independent of driving velocity, leading to greater acceleration and displacement of the neck. One notable example was abrupt stops – these driving tasks may appear innocuous yet yielded acceleration peaks that should encourage emergency personnel to limit their incidence. Progressive decelerations, which could be expressed as smoother driving, should be emphasized in drivers' training and encouraged when possible in emergency situations. The recommendation to reduce driving speed when turning is prudent and treatment times are unlikely to increase greatly from such minor adjustments, while the repercussions on patients should be beneficial to spinal precautions.

In other circumstances, however, it may be more difficult to modify driving behaviours to limit ambulance exposure to acceleration peaks. For example, a road feature such as a speed bump results in greater ambulance acceleration and H-N motion than most other tasks in this study – although SI proved to restrict motion of the neck better than SMR during this task, both conditions lead to considerable accelerations and displacements. One recommendation is to avoid such perturbations when possible, by planning routes devoid of traffic-calming measures, however in some cases this may not be feasible (e.g. residence located on street with traffic calming). Alternatively, municipal transportation/infrastructure departments may want to give special consideration to roadways commonly used by ambulances (main access routes, roads near hospitals), for which alternative methods of traffic calming could be considered over speed-bumps. It would also be beneficial to investigate the effects of other road-related conditions on ambulances (pot holes, loose gravel, dirt, etc.), as well as the effects of transitioning from one to the other at varying speeds, furthering the work of Tucker et al on utility medical vehicles[84]. Future studies should quantify driving across uneven road surfaces, and its effects on neck kinematics, in multiple planes. Finally, the inherent features of ambulances themselves may contribute to H-N motion and may not be modifiable. For instance, ambulance tires at each axle are likely to contact road irregularities at different times, inducing lateral motion to the vehicle (on top of the vertical displacement & accelerations) and resulting in asynchronous lateral acceleration of the participant's head. It is possible that poor road conditions may result in H-N motion in the frontal plane (lateral flexion) as well as in the sagittal plane (flexion/extension), hence the importance of multiple single-axis analysis.

Implications for spinal precaution devices

This study challenges the long-held belief that immobilizing a patient on a long backboard is necessary for providing spinal precautions in the prehospital setting. Further, the lack of a difference in H-N motion control between SI and SMR during the majority of ambulance transport is meaningful, as it challenges the 'protection' offered by both current approaches. Alternatively, rather than compare SI and SMR, perhaps patients with suspected spinal injuries would be best protected by some alternate protocol and/or device. For example, this study suggests that the cervical collar, used in both protocols, is limited in its ability to prevent rotation of the head. Recommendations have been made on how to improve head fixation, such as using sandbags[21], or a set of soft wedges in place of head blocks[21]. Their efficacy remains to be thoroughly investigated. In other cases, partial precautions via SMR may provide equal (sometimes superior) H-N motion control when compared to SI in conscious participants[14]. In fact, it may be possible that conscious, compliant patients require little external support beyond voluntary muscle control[89], which begs the question of why SI and SMR are the two widely considered options for spinal precautions. These findings warrant further research into a better neck bracing device and/or inclusion of a 'no precaution' condition to all future studies (to investigate the protection provided by voluntary control).

Second, the backboard itself is another aspect that could be improved. While immobilizing the head seems to be a main goal of SI, often substantial H-N motion can occur due to inadequate control of the trunk and lower body[21]. One option would be to improve the control of patients' trunks and legs, for which a few straps are not sufficient. Another option would be to use alternative backboards, such as the vacuum mattress[78]. This device may provide better in-line stabilization, as its greater coefficient of friction and improved fit to the patient's body, may be more suited to limiting sliding and shifting of the patient's trunk, hips and legs[111]. Finally, patient positioning appears to be worthy of consideration. The SI protocol requires a fully supine position, aligning patients with the vehicle's longitudinal axis. In contrast, some SMR protocols allow for a semi-reclining position. In a semi-reclined position, the linear acceleration of the ambulance is now at a greater relative angle to the patient's anterior-posterior axis, in the direction of neck flexion-extension, potentially increasing the exposure of the H-N to more angular displacement. It is still unclear whether differences between SI and SMR are due to the equipment alone, or if patient positioning is indeed a factor in the amount of observed motion. Other considerations would include patient location relative to the ambulance itself: proximity to the vehicle's axles is likely a factor in acceleration exposure[96]. Traditionally, patients are loaded in the ambulance with their heads closest to the driver' seat, their feet being nearest to the ambulance backdoors. Comparing exposure of the neck to acceleration and displacement in both scenarios would help ensure this aspect of current protocols is indeed optimal.

Future studies

Future studies should address spine motion and outcomes in actual patients. The absence of objective kinematic data in actual patients experiencing spinal precautions remains a significant gap in the literature and one that limits the understanding of secondary injury mechanisms and best practice. The methodology used in this study, particularly the acceleration data, is ideally suited to the study of neck kinematics in real, non-life-threatening situations. Such data would allow for more generalizable results and will provide a more accurate idea of what occurs during common emergency procedures. Further, examining more than one parameter of neck kinematics seems essential. While displacement seems to be the primary outcome, others[108] have hypothesized that injury can results from movements characterized by small displacements but high forces (of which acceleration are a determinant). As it is a relatively novel measure in spinal precautions, other parameters of the acceleration signal such as integrals (a measure of "total" acceleration) could shed more light on task-specific acceleration characteristics. The area of spinal precautions is rapidly evolving: the methods and results here provide complimentary novel findings, building towards a better understanding of spinal precautions during a critical component of emergency care.

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Appendix 1. Supplemental Tables and Figures

Table 6. Main effects of driving task and speed on ambulance acceleration (RMS) during controlled driving tasks performed at 5 - 45 km/hr. Dashed lines indicate significant differences between tasks/speeds. M [95%CI] shown.

	acceleration, rms (m/s^2)
Task	
abrupt stop	4.26 [3.76, 4.75]
speed bump	2.64 [2.26, 3.03]
turn	2.56 [2.47, 2.65]
s-turn	2.21 [2.12, 2.29]
abrupt start	2.05 [1.83, 2.27]
decelerating	1.82 [1.71, 1.93]
accelerating	1.46 [1.41, 1.51]
Speed (km/hr)+	
5	2.98 [2.77, 3.12]
45	3.09 [2.93, 3.25]
35	2.48 [2.39, 2.58]
25	1.65 [1.59, 1.70]
15	1.04 [1.00, 1.08]

Table 7. Main effects of driving task and speed on neck acceleration (RMS) in patients receiving spinal precautions during controlled ambulance transport tasks. Dashed lines indicate significant differences between tasks for SI & SMR comparisons (p<.05). M [95%CI] shown.

	H-N acceleration, rms (m/s^2)			
Task	**SI & SMR**	**SI**	**SMR**	**p**
speed bump	2.20 [1.64, 2.75]	1.87 [1.13, 2.60]	2.53 [1.63, 3.43]	>.13
abrupt stop	1.85 [1.42, 2.28]	2.03 [1.30, 2.76]	1.68 [1.17, 2.19]	>.21
turn	1.14 [1.07, 1.20]	0.96 [0.90, 1.02]	1.31 [1.21, 1.42]	<.001
s-turn	1.06 [0.99, 2.28]	0.89 [0.8, 0.99]	1.22 [1.10, 1.35]	<.001
abrupt start	0.82 [0.68, 0.97]	0.97 [0.69, 1.24]	0.68 [0.56, 0.81]	<.05
decelerating	0.79 [0.72, 0.87]	0.80 [0.68, 0.93]	0.78 [0.70, 0.87]	>.39
accelerating	0.49 [0.45, 0.53]	0.44 [0.39, 0.49]	0.54 [0.47, 0.61]	<.05
Speed				
5	1.63 [1.39, 1.86]	1.62 [1.28, 1.96]	1.63 [1.30, 1.97]	>.45
45	1.19 [1.09, 1.29]	1.12 [0.95, 1.28]	1.26 [1.15, 1.38]	>.07
35	1.04 [0.97, 1.11]	0.94 [0.85, 1.02]	1.14 [1.03, 1.25]	<.01
25	0.73 [0.69, 0.78]	0.64 [0.59, 0.70]	0.83 [0.75, 0.91]	<.001
15	0.55 [0.50, 0.59]	0.46 [0.42, 0.50]	0.64 [0.55, 0.72]	<.001

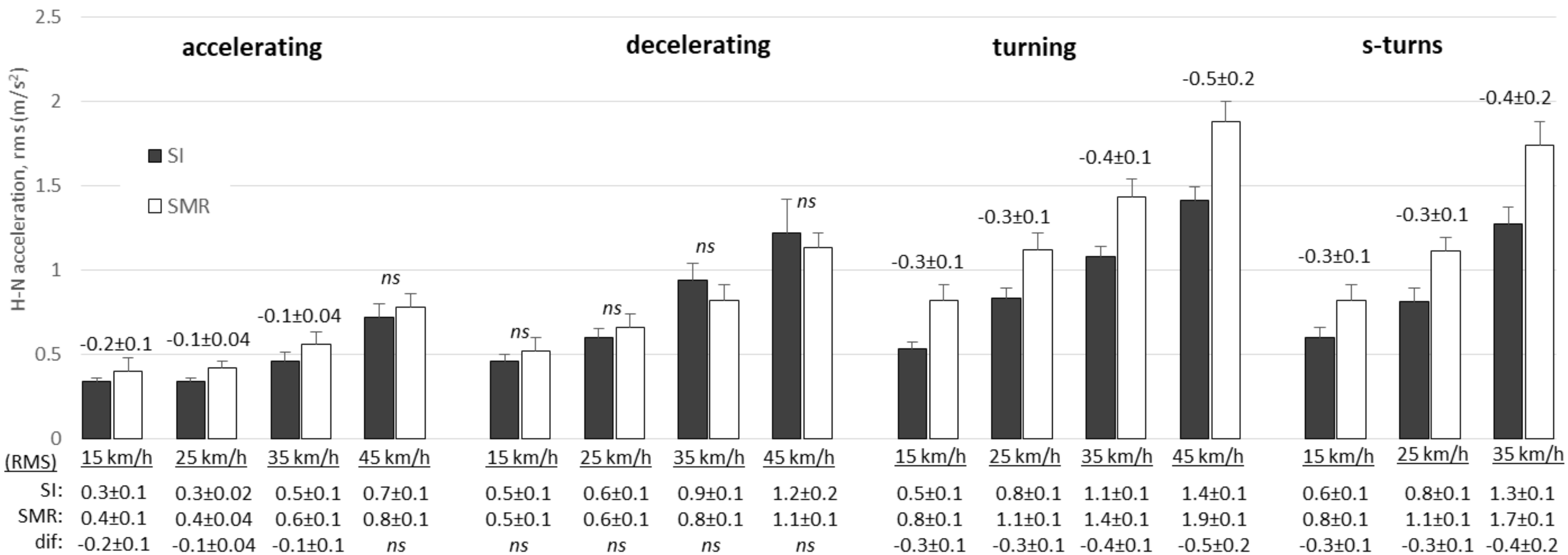

Figure 3.Effect of immobilization condition (SI vs SMR) on head-neck acceleration (RMS) during accelerating, decelrating, turning and s-turn tasks performed at 15, 25, 35 and 45 km/hr. Data labels (above bars) indicates difference.

Table 8. Main effects of driving task and speed on H-N acceleration (crest factor) in patients receiving spinal precautions during controlled ambulance transport tasks. Dashed lines indicate significant differences between tasks for SI & SMR comparisons (p<.05). M [95% CI] shown.

	acceleration (crest factor)			
Task	SI & SMR	SI	SMR	p
speed bump	4.55 [3.99, 5.11]	4.82 [3.87, 5.77]	4.28 [3.59, 4.96]	>.17
abrupt stop	2.40 [2.19, 2.61]	2.82 [2.43, 3.21]	1.98 [1.82, 2.14]	<.001
turn	4.06 [3.88, 4.24]	3.90 [3.68, 4.13]	4.22 [3.94, 4.50]	<.05
s-turn	2.96 [2.80, 3.12]	3.37 [3.14, 3.61]	2.54 [2.33, 2.76]	<.001
abrupt start	2.44 [2.03, 2.84]	2.66 [1.89, 3.14]	2.21 [1.90, 2.53]	>.13
decelerating	3.21 [9.07, 3.35]	3.27 [3.06, 3.48]	3.16 [2.96, 3.35]	>.22
accelerating	2.87 [2.74, 3.00]	2.93 [2.74, 3.12]	2.81 [2.62, 3.00]	>.18
Speed				
5	3.13 [2.89, 3.36]	3.43 [3.03, 3.84]	2.82 [2.57, 3.07]	<.05
45	3.09 [2.89, 3.29]	3.06 [2.77, 3.35]	3.12 [2.81, 3.43]	>.39
35	3.14 [3.00, 3.28]	3.26 [3.05, 3.47]	3.03 [2.85, 3.20]	<.05
25	3.45 [3.32, 3.59]	3.58 [3.39, 3.76]	3.32 [3.14, 3.51]	<.05
15	3.45 [3.30, 3.61]	3.50 [3.31, 3.69]	3.41 [3.16, 3.66]	>.28

Table 9. Linear regression models predicting head-neck displacement (left) and head-neck acceleration (right).

dependent variable:	displacement, H-N (total)			acceleration, H-N (peak)		
	B±SE	Std B	Sig.	B±SE	Std B	Sig.
Constant	16.99±3.00		<.001	-0.51±0.88		>.55
Ambulance acc, peak	0.91±0.20	0.25	<.001	0.91±0.06	0.68	<.001
Ambulance acc, rms	1.90±0.48	0.22	<.001	0.12±0.14	0.04	>.39
Ambulance speed	0.12±0.03	0.15	<.001	-0.53±0.01	-0.18	<.001
Neck length	-0.85±0.20	-0.16	<.001	--	--	--
			$r = 0.50$; $R^2 = 0.25$			$r = 0.71$; $R^2 = 0.50$